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Microstructure, mechanical properties and formability of friction stir processed interstitial-free steel

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ABSTRACT

The microstructure, mechanical properties and stretch formability of fine-grained (FG) interstitial-free steel (IF-steel) formed by friction stir processing (FSP) was investigated systematically. One-pass FSP drastically refined the microstructure with aid of dynamic recrystallization (DRX) mechanism during processing and formed volumetric defect free basin-like processed region (PR) with a mean grain size of 5 μm (initial grain size was 40 μm). This microstructural evolution brought about a considerable increase in both hardness and strength values of IF-steel without considerable decrease in ductility values. Also, strain hardening dominated deformation behavior was obtained with the FSPed samples as an essential property for the engineering application. Coarse-grained (CG) IF-steel demonstrated high formability with an Erichsen index (EI) of 2.88 mm. Grain refinement by FSP yielded very close EI value of 2.80 mm with increasing punch load (F_{EI}). Force–displacement curves obtained in each process conditions reflected a similar membrane straining regimes where samples uniformly thinned under biaxial tension loads with aid of strain hardening capability. The formation of FG microstructure by FSP reduced the roughness (orange peel effect) of the free surface of biaxial stretched sample by decreasing the non-uniform grain flow leading to the so-called orange peel effect. It is concluded that a good balance of strength, ductility and strain hardenability along with equivalence formability to CG condition can be achieved by FSP as a single step practical procedure.

1. Introduction

Friction stir processing (FSP) is a novel surface engineering technique developed based on the principles of friction stir welding (FSW) [1,2]. In FSP, a non-consumable rotating tool with a shoulder and pin is inserted into a metal plate and traversed through a direction of interest. Heat generated by the friction between rotating tool and metal surface locally softens the volume to be processed. By traversing the rotating tool, the material flowing around the pin and the tool shoulder undergoes severe plastic deformation and thermal exposure [3]. Mainly, plastic deformation with frictional heating upto 0.6–0.7 T_m leads to dynamic recovery (DRV) and dynamic recrystallization (DRX) assisted microstructural refinement [4–6]. In many cases, the FSP leads to transformation of the coarse-grained (CG) initial microstructure into equiaxed fine-grained (FG) and/or even ultra-fine grained (UFG) structure mostly consisting of high angle grain boundaries (HAGBs) [1–5,7]. On the other hand, dendritic structure of the as-cast alloys can be successively broken-up, and casting defects like solidification micro-porosities, cavities and inclusions are eliminated with FSP [6,7]. Furthermore, this method has been successfully used for producing metal matrix surface composites on plate-type samples. Incorporation of reinforcement components like ceramic particles, multi-walled carbon nanotubes into the metal matrix have been done with the aid of intense plastic deformation and stirring during FSP [1,2].

It can be said that microstructural investigations have been extensively undertaken for the FSPed materials. Given the potential technological advantages of this effective and flexible technology, several research efforts have been made to understand the mechanical response and engineering performance of the FSPed materials. To date, considerable attention has been paid especially to the light metals namely wrought and cast Al, Mg, Cu and Ti alloys [1,2,8]. It has been demonstrated in these studies that mechanical properties of CG metallic materials could be enhanced by microstructural refinement and re-organization [1,2,8]. Generally,

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enhanced hardness and strength can be achieved for variety of material groups according to Hall–Petch type strengthening [1,2,8,9]. Softening of the precipitation-hardenable Al alloys, on the other hand, was reported due to the coarsening and dissolution of the precipitates as a result of the heat generated during FSP [10,11]. A simultaneous increase in strength and ductility was achieved with FSPed as-cast alloys, i.e. Al–Si alloys, as a result of structural refinement and elimination of the casting defects and breakage of dendritic microstructure [6,12–14]. Also, as-cast Mg and Al alloys showed better superplasticity at lower deformation temperatures and higher strain rates after FSP [15–17]. It was also reported that room temperature formability of Al5052-H32 [18] and AZ31 [19,20] alloys was improved by FSP.

As looking at the literature, less attention has been given to the processing of body-centered cubic (BCC) steels by FSP despite their significant industrial applications. In limited studies, mainly microstructural evolution and texture formation of FSPed steels were investigated [3,21–24]. It has been reported that the microstructures of FSPed steels consisted of nearly equiaxed grains with the sizes of micron levels [3,25]. Also, hardness of FSPed steels increased in the nugget zone (NZ) compared to that of the base material [3,21–24]. The effect of microstructural evolution on the strength and ductility of the FSPed steels was rarely reported. In a recent study, it was shown that plain low carbon steel subjected to FSP under rapid water cooling brought about a higher strength with a considerably high ductility compared to the quenched counterpart [22].

In view of above, further investigations are needed to identify the mechanical properties of the FSPed steels in order to reveal possible advantages of FSP on the strength and ductility. To the author's best knowledge, on the other hand, the effect of FSP on the formability of steels has not been investigated yet. Therefore, the purpose of this study is to investigate systematically the effect of microstructural evolution by FSP on the strength, ductility and formability of single-phase ferritic steels (IF-steel). Furthermore, the formability of the FSPed IF-steel (as a model material) was evaluated. This study has a potential to become a base for other studies in the formability of FSP-induced materials to be performed in future.

2. Experimental procedure

Cold rolled and continuously annealed IF-steel sheets having the chemical composition of 0.004 wt% C, 0.012 wt% Si, 0.2 wt% Mn, 0.012 wt% P, 0.009 wt% S, 0.1 wt% Ti and balance Fe was used in this study. Samples with the dimensions of 200 mm × 60 mm × 2 mm were cut from the as-received CG sheets. They were subjected to one-pass FSP using a WC tool consisting of a convex shoulder having a diameter of 16 mm and a cylindrical pin with a diameter and length of 5 mm and 1 mm, respectively (Fig. 1). Tool rotation speed and processing speed was set at 800 rpm and 65 mm/min, respectively. The shoulder tilt angle was 3°, and the tool plunger downforce were kept constant at 7 kN. Processing temperature was determined with a thermocouple placed in the vicinity of the processing surface of a dummy sample. Peak temperature was determined to be 760–800 °C which is lower than that of ferrite–austenite transformation temperature (≈ 910 °C).

Scanning electron microscope (SEM) and optical microscope (OM) were used to observe the microstructure of IF-steel samples before and after FSP. The metallographic specimens were sectioned perpendicular to the process direction (Fig. 1) and then etched in 2% Nital for 20 s after standard metallographic preparation. In order to reveal the microstructural details, electron backscattering diffraction (EBSD) was also performed on the processing plane (Fig. 1).

Hardness measurements were performed using a Vickers micro-hardness tester under a load of 200 g and for 10 s dwell time (Fig. 1). Tensile properties were determined on dog bone-shaped specimens with gauge section of 0.8 mm × 3 mm × 26 mm at a strain rate of 5.4×10^{-4} s^{-1}. The tensile axis of the samples was oriented parallel to the processing direction (Fig. 1). At least three tests were conducted to check the repeatability of both hardness and tensile test results for each point.

Stretch formability tests before and after FSP were performed using the Erichsen test technique, which is a well-established standard for studying the formability under biaxial strain conditions. The Erichsen test specimens with the dimensions of 13 mm × 13 mm × 0.7 mm were sectioned from the FSPed zone (Fig. 1). Specimen surfaces were prepared by grinding and polishing before FSP to avoid crack initiation effect of tool scars. The tests were performed using a miniaturized Erichsen die system attached to an Instron 3220 universal testing machine with a punch speed of 0.01 mm s^{-1} without lubrication. The dimensions of test die were chosen as 25% of standard Erichsen test fixture according to ISO-EN 20482 (Fig. 1(b)). After the test, the Erichsen Index (EI) and the load (F_{EI}) corresponding to this index were determined. At least three tests were performed for each curve to check the repeatability of the test results.

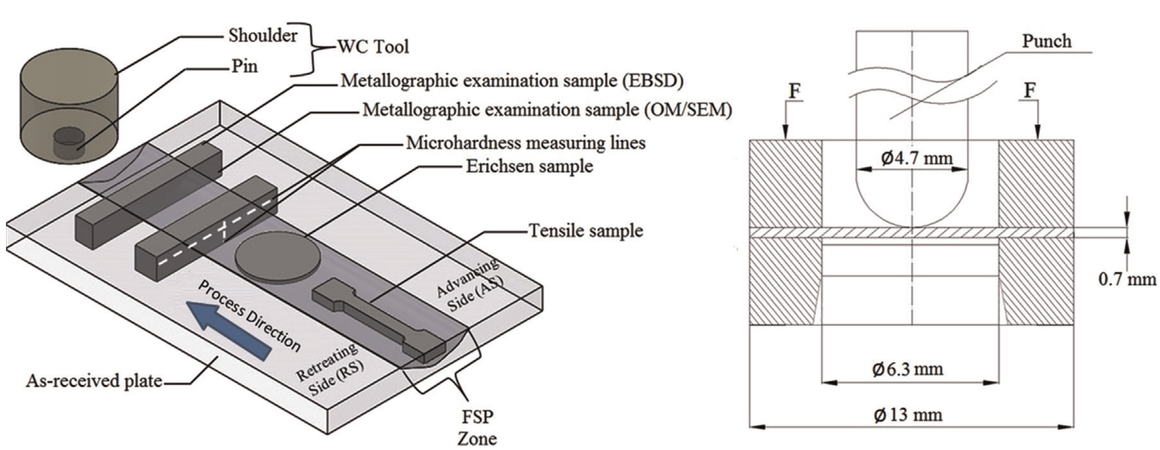

Fig. 1. (a) Schematic illustrations of the FSPed plate and the position of the specimens inside the FSPed zone. (b) Miniaturized Erichsen die set.